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**CENTER OF EXCELLENCE IN
COMMAND, CONTROL, COMMUNICATIONS AND INTELLIGENCE**

**GEORGE MASON UNIVERSITY
Fairfax, Virginia 22030**

QUARTERLY TECHNICAL REPORT

for the period

16 March 1991 - 15 June 1992

for

**THE IMPACT OF ORGANIZATION STRUCTURE ON TEAM
DECISION MAKING UNDER STRESS AND UNCERTAINTY**

Grant Number N00014-90-J-1680
R&T Project Number URI 5202-9003

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August 3, 1992

Report #: GMU/C3I-121-IR

1. PROGRAM OBJECTIVES

The objective of this research is to investigate coordination in hierarchical team decision making. Particular focus is placed on the identification and characterization of variables that enhance coordination and enable teams to maintain coordinated action under stressful conditions characteristic of tactical environments.

2. STATEMENT OF WORK

The research proposal identified three major project tasks which define a sequence of three team decision making experiments. Each experiment involves the combined use of analytic models of the experimental setting and psychological models of human behavior to design the experiment and to predict performance.

Year 1 Experiment - The Year 1 experiment expands on the work of Jin (1990). The experiment will investigate the effects of time stress on team decision making performance. The experiment will be hosted on the testbed developed by Jin at MIT.

Year 2 Experiment - This experiment will focus on issues related to fixed versus variable structure organizations.

Year 3 Experiment - This experiment will extend the results of the previous experiments.

3. RESEARCH PLAN

The research plan describes our strategy for meeting the program objectives and fulfilling the project tasks. Specifically the research plan identifies a series of specific research tasks. The research plan will evolve during the duration of this effort.

The plan for the first two years of this research program was organized into three highly related research areas:

- (a) Analytical models of C3I organizations that incorporate coordination variables,
- (b) Descriptive models of team decision making.
- (c) Prescriptive models of team decision procedures.

As a result of our progress in these areas, a fourth research area was introduced in an earlier progress report that integrates the approaches in areas (a) and (c):

- (d) Prescriptive models of adaptive C2 organizations.

This new area is a natural evolution of the research program and represents an effort to merge together results from the cognitive and the engineering aspects of the research; this is the natural next step towards the development of a theory of C2 organization design that encompasses both fixed and variable structures.

Each of these areas is discussed briefly below. A detailed discussion of the individual tasks is provided in subsections 4.1 through 4.9.

The focus of the first area is the development of methodologies, models, theories and algorithms directed toward the derivation of tactical decision, coordination, and communication strategies of agents in organizational structures. Both fixed and variable organizational structures are

considered. However, the focus is on modeling variable organizational structures and how those structures adapt under conditions of stress. The framework for this research is analytic. The following tasks address this research area:

4.1 Coordination in Decision Making Organizations

4.2 Design of Multilevel Hierarchical Organizations.

The focus of the second area is the development of descriptive models of human decision making that are relevant to predicting team decision making performance under stress. For this work, it is assumed that the team members are well-trained. Consequently, the focus of the research is to identify conditions under which team performance degrades because one or more team members cannot effectively execute trained procedures properly. The following tasks address this research area:

4.4 Experimental Research to Evaluate Vulnerable-to-bias Decision Procedures

4.6 Quantitative Models of Combined User/Decision Aid Performance.

The focus of the third area is to develop a prescriptive methodology for specifying team decision making procedures. This work combines the normative and descriptive research in the first two areas to develop a methodology for deriving a set of robust team decision procedures. This includes procedures for coordinating team decision making activities and adaptation of coordination procedures. The following tasks address this research area:

4.3 Methodology for Prescribing Team Decision Procedures

4.5 Automated Tools for Specifying Decision Procedures

The fourth area reflects an integration of the results obtained in the previous three research areas. Specifically, this research area addresses the problem of developing an integrated procedure that moves from an initial prescription of decision making procedures (research area 3) to a detailed analytic model of the organization (research area 1). To address this problem, the following research tasks have been added:

4.7 Petri Net Representation of Team Decision Procedure

4.8 Organizational Coordination Model

4.9 Integration of System and Coordination Models.

Each of these research tasks are described in detail in the next section.

The nine tasks that constitute the scope of work of this project are inter-related, with the tasks in area four building upon the findings of the other tasks. Their relationship to each other is shown in Figure 3.1. The four tasks in Figure 3.1, distinguished by the patterned boundary, are the ones that have been completed and reports have been written or are in the last stages of preparation.

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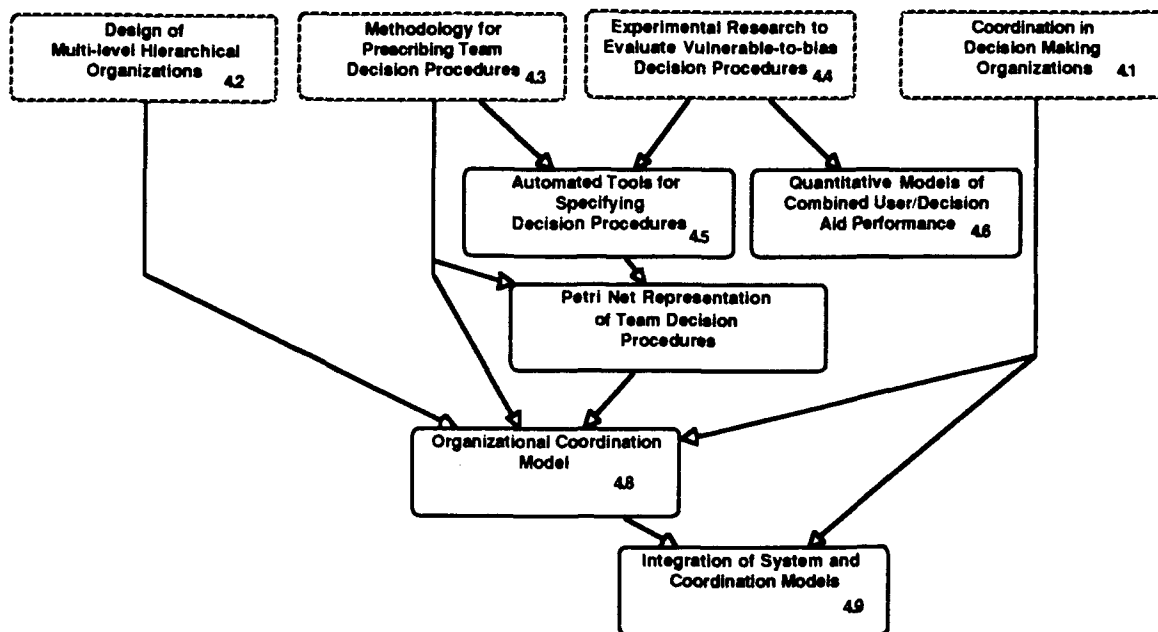


Figure 3.1 Inter-relationship of Research Tasks

4. STATUS REPORT

In the context of the three project tasks and research plan outlined above, a number of specific research tasks have been formulated. These are being addressed by project faculty and by graduate assistants under the direction of project faculty. Each research task is discussed below. In previous reports, detailed results for research tasks 4.1 through 4.4 were presented. In this report, we introduce three new research tasks 4.7 through 4.9.

4.1 Coordination in Decision Making Organizations

Background.

The concept of an organization embodies two meanings. One is the set of physical entities and the interactions between them. Another is the set of rules that govern the operation of a set of interacting physical entities. We call all these physical entities and their interactions the system, and we characterize the operation of the system as coordination.

A key question in modeling and designing organizations is whether these two concepts can be decoupled. Mr. Zhuo Lu has investigated this problem under the supervision of Prof. Alexander H. Levis and has produced a Master's Thesis published as a technical report.

Results to date.

A technical paper summarizing some a key result from this investigation is appended to this quarterly report. The thesis/report of Mr. Zhuo Lu is being submitted separately.

Documentation

1. Z. Lu and A. H. Levis, "A Colored Petri Net Model of Tactical Decision Making," *Proc. 1991 Symposium on C2 Research*, National Defense University, Ft. McNair, Washington, DC, June 1991.
2. Z. Lu and A. H. Levis, "A Colored Petri Net Model of Distributed Tactical Decision Making," *Proc. 1991 IEEE International Conference on Systems, Man, and Cybernetics*, October 1991.
3. Z. Lu, "Coordination in Distributed Intelligence Systems," MS Thesis, Report GMU/C3I-120-TH, C3I Center, George Mason University, Fairfax, VA.
4. Z. Lu and A. H. Levis, "Coordination in Distributed Decision Making," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics*, October 1992.

4.2 Design of Multi-level Hierarchical Organizations

Background. Both centralized and distributed organizations are characterized by their hierarchical structure. These organizational architectures are described by families of structures with each family concerned with the behavior of the organization as viewed from a different level of abstraction. Previous efforts under the Distributed Tactical Decision Making program resulted in a number of methodologies to design and generate architectures in which the system is viewed only from a single level of abstraction (Remy and Levis, 1988). The basic decision making entity assumed throughout these methodologies was a human decision maker (DM). This effort was directed towards a methodology to generate in some orderly manner organizational structures for *multilevel* hierarchical organizations. This research task was necessary if realistic decision making organizations are to be modeled and analyzed. A second benefit of this approach is that the dimensionality problem that prohibits the design of large organizations can be circumvented by solving a series of problems at different levels of abstraction. The research task has been carried out by Mr. Syed Abbas Zaidi under the supervision of Prof. Alexander H. Levis.

The following four issues have been addressed in order to implement such a methodology;

- (a) The concept of multilevel hierarchical organizational structures was formulated analytically.
- (b) A mathematical framework that is appropriate for the formulation of the design problem was identified.
- (c) Sets of constraints were identified for different levels in the organization to reflect design requirements and to keep the problem of generating organizational structures computationally feasible.
- (d) A set of connectivity rules were formulated in order to integrate organizational structures defined at different levels of abstraction.

Results to Date

The previous two quarterly reports outlined the findings of research done on these four issues. During this quarter, the thesis was re-edited to produce a technical report suitable for distribution. It was distributed in May 1992.

Mr. Zaidi and Prof. Levis have documented some of the results of this task in a technical paper for presentation at the 1992 IEEE International Conference on Systems, Man and Cybernetics, to be held in Chicago, IL in October 1992.

Documentation

1. A. H. Levis, "A Colored Petri Net Model of Intelligent Nodes" *Proc. 1991 IMACS Symposium on Modeling and Control of Technological Systems*, Lille, France, May 1991. The paper was also selected to appear in a book by Elsevier - North Holland with selected reprints from several IMACS symposia. Book to appear in 1992.
2. A. H. Levis, "A Colored Petri Net Model of Command and Control Nodes" to appear in *Command, Control, and Communications: Advanced Concepts and Paradigms*, Carl R. Jones, Ed., AIAA Press, Washington DC. Book to appear in late 1992.
3. S. A. K. Zaidi, "On the Generation of Multilevel, Distributed Intelligence Systems using Petri Nets," MS Thesis, Report GMU/C3I-113-TH, C3I Center, George Mason University, Fairfax, VA. May 1992.
4. S. A. K. Zaidi and A. H. Levis, "Algorithmic Design of Multilevel Organizational Structures," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics*, October 1992.

4.3 Methodology for Prescribing Team Decision Procedures

Background. A team is a well-trained group of decision makers with overlapping areas of expertise. Each team member has an area of responsibility, a set of decision functions for which that team member is responsible, and a protocol for communicating with other team members. Previous work in the mathematical modeling of teams has addressed the problem of specifying organizational structures, but there has been very little work addressing the problem of specifying the procedures embedded in each decision function.

In team decision making, a function corresponds to a set of decision procedures. For instance, a team member may be responsible for the function Interpret-Sensor-Readings, where it is the team member's responsibility to read a set of sensor displays (input) and to report values for Probable-Current-Situation (output). Another team member may be responsible for the function Allocate-Air-Resources, where it is the team member's responsibility to use information about the Probable-Current-Situation to determine how to allocate air resources.

The performance of a team depends on the decision procedures each team member has been trained to execute and how effectively and reliably those procedures are executed. The objective of this research activity is to develop an approach to prescribing a set of decision procedures that (a) will lead to high performance, and (b) team members can reliably execute even under conditions of high stress.

Progress to date.

A general approach for prescribing team decision procedures was described in an earlier progress report and presented at the 1991 BRG symposium. This general approach focused on the use of probability models of decision situations and derives decision procedures from these models.

During this period, a general procedure for incorporating utility information was defined. This is described in detail as part of task 4.5.

Documentation

1. P. Lehner, "Towards a theory of team design," *Proceedings of the 1991 Symposium on Command and Control Research*, June 1991, 149-159.
2. P. Lehner, "Towards a prescriptive theory of team design," *Proceedings of the 1991 IEEE Conference on Systems, Man and Cybernetics*, September 1991, 2029-2034.
3. P. Lehner, "A prescriptive methodology for deriving team decision procedures," working paper, George Mason University, Fairfax, VA. April 1992.

4.4 Experimental Research to Evaluate Vulnerable-to-bias Decision Procedures

Background. C2 teams are composed of a group of interacting decision makers working cooperatively to solve a common decision problem. Each team member has an area of expertise. Each team member is responsible for a distinct set of inference and decision functions for which each team members is well-trained. Under conditions of low stress, one would expect a well-trained team to reliably execute the procedures they have been taught and to perform well. An open question, however, is the extent to which training breaks down under conditions of high stress. Except for issues related to task workload, this issue has not been addressed.

The objective of this research task is to investigate the impact of cognitive biases on the performance of well trained teams under stress. Our research contrasts two perspectives.

Perspective 1 (P1) - Cognitive biases are largely a matter of preference. Although people tend to use heuristic rules that deviate from normative procedures, they can be taught to reliably use alternative rules, as long as the alternative rules do not exceed bounded rationality constraints.

Perspective 2 (P2) - Cognitive biases are largely a matter of capability. Even if trained, people do not reliably execute judgment and decision procedures that do not conform to cognitive biases.

For team decision making under stress, these two perspectives differ considerably with respect to their implication for designing teams. If P1 is correct, then the literature on human cognitive biases is simply irrelevant to the problem of designing teams. Properly trained and practiced teams will reliably execute correct decision procedures until workload or other bounded rationality constraints are exceeded. If P2 is correct, then cognitive bias considerations should place severe constraints on the design of a team. Specifically, one should avoid specifying team architectures and decision procedures that are inconsistent with the heuristic decision making procedures that people naturally use. Otherwise, these teams will be vulnerable to cognitive biases, and the team's decision procedure will not be executed reliably under high stress conditions.

Several experiments investigating this issue will be performed.

Progress to date.

The principal results of the first experiment were summarized in the previous progress report. A report on this experiment was distributed in early May.

An initial design for the second experiment was generated. The focus of this experiment will be on the extent to which team members appropriately adapt their decision procedures to increasing time stress. Our hypothesis is that under time stress, subjects will inappropriately adapt by sometimes ignoring the advice of other team members, even when this inappropriate adaptation leads to a decrease in performance and, perhaps, an increase in workload.

This research will be conducted by Mathew Christian under the direction of Dr. Lehner. Mr. Christian is an undergraduate senior who will be entering the Systems Engineering graduate program in Spring 1993. We expect to be running pilot subjects during the next period.

Documentation

1. P. Lehner, B. Nallappa, M. O'Conner, S. Saks, and T. Mullin, "Cognitive Biases and Stress in Team Decision Making: Preliminary Report," *Proceedings of the 1991 Symposium on Command and Control*.
2. P. Lehner, M. Seyed-Solorforough, B. Nallappa, M. O'Conner, S. Saks, and T. Mullin, "Cognitive Biases and Time Stress in Team Decision Making," GMU-C3I Center Technical Report (number pending), May 1992.
3. M. O'Conner, "Cognitive Biases: A Perspective and Recommendations," GMU-C3I Center Technical Report (number pending), October 1991.

4.5 Automated Tools for Specifying Decision Procedures

Background. The objective of this task is to develop automated tools to *derive* team decision procedures from a domain model represented as an influence diagram. The input to the tool will be a domain model and (optimally) a proposed team architecture. The proposed architecture includes both the number of team members and the types of information flows among team members. The automated tools will tradeoff several factors in the specification of these procedures. These factors include expected performance, workload and cognitive biases.

This research is being performed by Azar Sadigh under the direction of Dr. Lehner.

Progress to date. A general mathematical framework for evaluating a proposed team decision procedure was described in a previous progress report.

During this period, an analytic procedure for deriving team decision procedures was developed. This analytic procedure is explained below.

We begin by defining some basic terms. Figure 4.5-1 depicts a small decision network (a.k.a. influence diagram). The circle nodes are *chance nodes*. Each chance node identifies an exhaustive set of mutually exclusive propositions. The arcs between chance nodes identify the conditional probability statements that must be contained in each node. For instance, the node Typ contains the unconditional probability distribution $P(\text{Typ})$. The node A contains the conditional probability distribution $P(A|\text{Typ})$. The rectangular node is a *decision node*. Each decision node identifies an exhaustive set of mutually exclusive decisions that could be made. Arcs going from a chance node to a decision node are information arcs. They identify

information that will be available when the decision must be made. The diamond node is a *value node*. A value node assigns a utility to each row in the cross product of the propositions/decisions of its parent nodes. For instance, the node Val in Figure 4.5-1 assigns a utility (d1,t1), (d1,t2), (d1,t3), (d2,t1), ...

In this paper, chance nodes that have information arcs going to a decision node are referred to as *evidence items*. An evidence item is *instantiated* when the value of that evidence item is known. For instance, A=a1 asserts that the *evidence item value* for node A is a1. A set of evidence item values for all evidence items is referred to as an *evidence state*. For instance, the vector <a1,b2,c3> describes the evidence state where A=a1, B=b2 and C=c3.

Once a decision network has been defined, there are a variety of algorithms and software tools for processing the network (Buede, 1992). These algorithms can be used to derive the expected utility of any decision, or the posterior probability of any chance node, conditioned on specific values for any subset of the chance nodes.

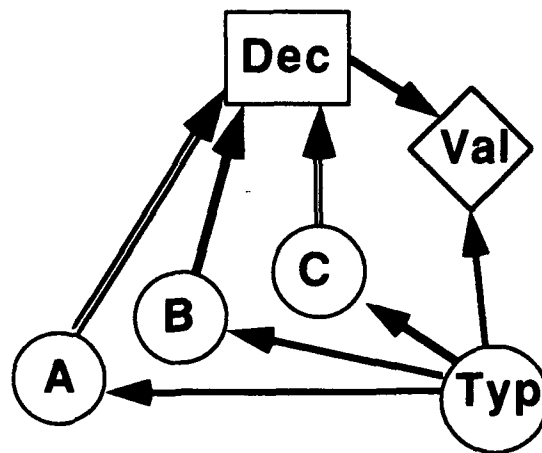


Figure 4.5-1. A Decision Network

Default Trees

We define a *default tree* (DTree) as a tree composed of decision nodes (Dnodes) and evidence nodes (Enodes). Each Dnode specifies a decision, while each Enode specifies an evidence item. To illustrate, the DTree in Figure 4.5-2 contains 4 evidence nodes and 6 decision nodes. This DTree corresponds to a decision procedure where the DM first examines A. If A is a2, then the decision d1 is immediately selected. If A reads a1, then the decision maker examines B. If B reads b1, then the decision d1 is selected, else if B=b2 then d2 is selected. Returning to Enode {A}, if A=a3 then C is examined. If C=c1, then d1 is selected. If C=c2 then B is examined. If B=b1, then d2 is selected, otherwise d3 is selected. A DTree is the same as an asymmetric situation-action tree in Heckerman, et.al., (1989).

Dnodes are partitioned into two types: open and closed. A Dnode is *closed* if the path leading to the Dnode contains all the evidence items available. A Dnode is *open*, if it is not closed. Note that open Dnodes correspond to *default decisions*, since they specify decisions that may change if additional evidence is examined.

More formally, we can characterize a DTree as follows. Let DN be a decision network which contains a decision node D and a set of evidence nodes $\{E_i\}$. Let $\{N_i\}$ be a collection of nodes in DT, a specific DTree. Each N_i can be an open Dnode, a closed Dnode, or an Enode. The following predicates are defined with respect to DT.

$path_{DT}(N_i)$ - The conjunction of evidence item values in the ancestors of N_i . (e.g., $path_{DT}(N_5) = (A=a_2 \wedge B=b_1)$).

$evid-path_{DT}(N_i)$ - The evidence items that are listed in the ancestors of N_i (e.g., $evid-path_{DT}(N_5) = \{A, B\}$). For the root node, $evid-path_{DT} = \{\}$.

$dec_{DT}(path_{DT}(N_i))$ - The maximum expected utility decision in DN given the evidence item values leading to N_i . That is, $dec_{DT}(path_{DT}(N_i)) = \max_{d \in \{D_i\}} [EU(d|path(N_i))]$. (e.g., $dec_{DT}(path_{DT}(N_5)) = d_1$).

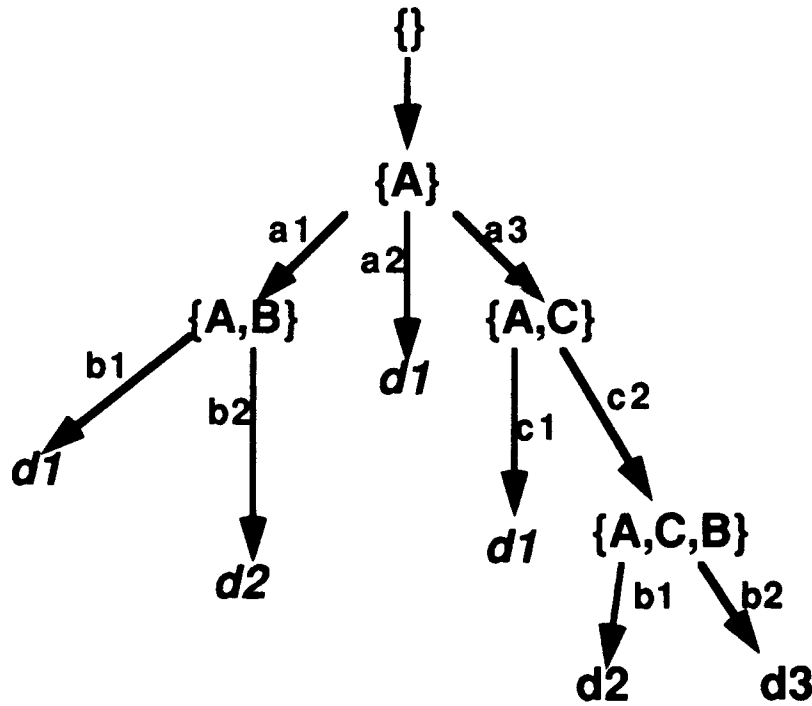


Figure 4.5-2. A Default Tree (DTree).

$evoid_{DT}(E|path(N_i))$ = The increase in expected utility for evidence item E in DN given the path to N_i . Formally,

$$evoid_{DT}(E|path(N_i)) = (\sum_{e \in EP(e|path_{DT}(N_i))} EU[dec_{DT}(E = e \wedge path_{DT}(N_i))]) - EU[dec_{DT}(path_{DT}(N_i))].$$

$max-evoid_{DT}(N_i)$ - The evidence node, E, for which $evoid_{DT}(E|path_{DT}(N_i))$ is maximal in DN.

$eu-expand_{DT}(Ni)$ - The increase in the expected utility of DT that is obtained by replacing $dec_{DT}(path(Ni))$ with the Enode that contains the $max-evoi_{DT}(Ni)$ evidence node. Formally,

$$eu-expand_{DT}(Ni) = P(path_{DT}(Ni)) \cdot evoi_{DT}(max-evoi_{DT}(Ni) | path(Ni))$$

Definition (DT-compile)

A DTree (DT) DT-compiles a decision network (DN) iff every evidence state in DN will lead to a Dnode in DT.

The DTree in Figure 4.5-2 DT-compiles the decision network in Figure 4.5-1.

Theorem 1. (DTree Expected Utility).

If a DTree (DT) DT-compiles a decision network DN, then the expected utility of the DT, with respect to DN, is

$$\sum_{N \in \text{Enodes}(DT)} eu-expand_{DT}(N).$$

The proof for both theorems is found in Lehner and Sadigh (1992).

Deriving DTrees

The following algorithm can be used to derive a sequence of increasingly complex DTrees.

Algorithm DD

- I. Let $N1 = \{ \}$.
- II. Add $dec()$ as a subnode to $N1$.
- III. Iterate through the following procedure
 - A. Select the Open Dnode for which $eu-expand_{DT}$ is maximal. Call this node N .
 - B. Set N equal to the Enode $evid-path_{DT}(N) \cup \{max-evoi_{DT}(N)\}$.
 - C. For each possible value (e) of $max-evoi_{DT}(N)$ add as a subnode to N
 $dec(path_{DT}(N) \& max-evoi_{DT}(N)=e)$.
 - D. Check stopping criterion. If Stop, then exist with current Dtree.
 - E. Go to A.

In words, DD iteratively replaces a default decision with the evidence item that maximizes the increase in the expected utility of the DTree, and adding as subnodes the Dnodes that correspond to the best decisions for each possible value of that evidence item.¹ This algorithm is consistent with the situation-action tree development algorithm described informally in Heckerman, et al. (1989).

DD is a greedy algorithm. At each iteration, it expands the DTree by adding and expanding the node that has the greatest increase in the expected utility of the DTree. Although DD is a greedy algorithm, it has useful optimality properties.

¹Obviously, the efficiency of DD could be increased substantially by recording the results of the $evoi$ calculations and keeping track of open and closed Dnodes. However, efficiency improvement will not change the order in which the DTree is expanded. Consequently, they are not presented here.

Definition. (E-descending)

DT is an E-descending DTree iff for every open Dnode (D), and evidence item (E),

$$P(\text{path}(D))\text{evoi}_{DT}(E|\text{path}(D)) \geq P(\text{path}(D) \cup \{e_i\})\text{evoi}_{DT}(E|\text{path}(D \cup \{e_i\})),$$

where $\{e_i\}$ is any set of evidence node values.

In words, a DTree is E-descending iff one cannot increase the *eu-expand*_{DT} value of adding an evidence item (E1) by delaying its insertion, adding one or more other evidence items instead, and then adding E1 deeper in the DTree.

Theorem 2. (Optimality of DD).

If each DTree generated by DD is E-descending, then each DTree generated by DD is optimal in the sense if DTx is generated by DD and another DTree (DTy) does not have more Enodes than DTx, then

$$EU(DTx) \geq EU(DTy).$$

It is worth noting that E-descending does not seem to be strong property and violations of it are often easy to detect. This is explained below.

It is possible that for a Dnode (D) the increase in expected utility of an evidence item (A) will increase if a path of evidence values $\{e_i\}$ are inserted as ancestors to A. However, in order to violate E-descending, it must be the case that

$$\text{evoi}_{DT}(E|\text{path}(D \cup \{e_i\})) > \frac{\text{evoi}_{DT}(E|\text{path}(D))}{P(\{e_i\}|\text{path}(D))}.$$

That is, the *evoi*_{DT} value must increase by a multiplier of more than $1/P(\{e_i\}|\text{path}(D))$. This can only occur if the change in the *evoi*_{DT} value is substantial or if $P(\{e_i\})$ is near one. $P(\{e_i\})=1$ is particularly unlikely if $\{e_i\}$ involves more than one evidence item. Consequently, violations of E-descending are probably infrequent and most violations that do occur can be anticipated by examining just two and three way interactions between the evidence items. We are currently developing a modified version of algorithm DD that accounts for such interactions. This will be reported in the next progress report.

Summary

In our current methodology Algorithm DD will be used to derive a DTree for an entire team. The procedures in the DTree will be partitioned using the techniques described developed in Tasks 4.7 - 4.9. However, once the partitioning has occurred, then the individual procedures can be modified by reapplying the algorithm.

We are currently exploring several improvements to algorithm DD for problems that involve violations of the E-descending property, multiple decision and time-varying value of information.

Documentation.

1. P. Lehner, P. and A. Sadigh, "Reasoning under uncertainty: Some Monte Carlo results." in *Uncertainty in Artificial Intelligence: Proceedings of the Seventh Conference (1991)*. San Mateo: Morgan Kaufmann Publishers, 1991, 205-211.
2. P. Lehner, and A. Sadigh, "A procedure for compiling influence diagrams," in *Proceedings of the 1991 Symposium on C2 Research*, May 1991.

4.6 Quantitative Models of Combined User/Decision Aid Performance

Background. The literature on DSSs is replete with long lists of features of a "good" decision aid. Unfortunately, despite all this advice, there are very few models that purport to predict the effect that introducing a decision aid into an decision maker's setting will have on performance. This task will investigate the development of quantitative models of the impact of introducing a DSS into a team's decision process. This work is an extension of the result in Lehner, et al. (1990) and the methodology described in research task 4.3 for deriving team decision procedures.

Progress to date. This work will be the Ph.D. Thesis of Mr. Thomas Lam under the supervision of Dr. Lehner. Mr. Lam is a program manager at DISA. He received a grant from DISA that will allow him to come to GMU full time in the Spring 1992 semester to work on his dissertation proposal.

Our general approach to modeling and predicting user/decision aid performance was presented at the C2 decision aids conference in June.

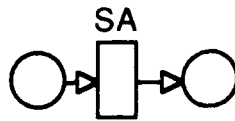
4.7 Petri Net Representation of Team Decision Procedures

Background. The objective of this task is to develop a methodology for deriving a Petri Net representation of the prescribed team decision procedure developed using the methodology described in research task 4.5. The resulting DTree is transformed into a Petri Net that represents the decisions to be made by the team and the information flow associated with the decision making process.

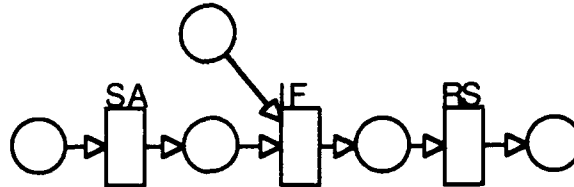
The work is being carried out by Mr. Didier Perdu, Mr. Diwakar Prabhakar, Mr. S. Abbas K. Zaidi and Ms. Zhenyi Jin under the direction of Dr. Levis.

Progress to Date: The problem was formulated as follows: *Given a DTree representing the Team Decision Process, generate the fixed structure(s) describing the functionality of the tree.* For each path in the DTree, starting from the root to one of the leaves (decisions), a fixed Petri Net structure is constructed, representing the rule in the decision process. Therefore, the total number of fixed structures equals the number of leaves. The algorithm for the generation of these structures is based on the two generic flow structures shown below. Different combinations of these structures can then be used to represent all the rules in the DTree, regardless of the number of items of evidence used in a rule.

Type 1



Type 2



An *ML/CPN* program has been developed, which accepts a DTree, drawn by the user using the existing *Design/CPN* utilities, and generates the executable fixed structures for each rule in the tree. This program was developed by Didier Perdu.

4.8 Organizational Coordination Model

Background. This research task is focused on the derivation of a variable structure organization that implements the team decision making procedure of task 4.7. Coordination involves a number of issues that are not readily apparent at the individual decision maker level. Of particular importance will be the development of a coordination model that guarantees that input and transmitted information to be sufficiently informative that individual decision makers will adapt to the current decision situation and execute appropriate decision procedures. (This relates directly to the notion of accessible alphabets from task 4.1.) That is, the coordination model must specify an efficient adaptation strategy.

Research on this task is being performed by Mr. Zhuo Lu and Mr. Ali Shah under the direction of Dr. Levis.

Progress to Date: The problem can be formulated as follows: *Given the fixed structures from Task 4.7, generate variable structure and check their feasibility.* Different folding schemes yield different variable structures. Protocols of folding the fixed structures into a variable structure must be specified; this is the current research issue. All possible folded structures, however, can be checked by the algorithm developed by Zhuo Lu in his thesis (Task 4.1), which checks the *coordination constraints*. The algorithm is being implemented by Mr. Z. Lu and Mr. Ali Shah. Folding of the structures corresponds to the grouping of different functions/sub-tasks/missions.

4.9 Integration of System and Coordination Models.

Background. Research tasks 4.7 and 4.8 result in a Colored Petri Net model of a variable structure that describes the prescribed set of team decision procedures. To complete the design, the tasks need to be allocated to Decision Making Units - either single decision makers or small organizational units. An interesting aspect of this work is that the model of Migration of Control (Levis and Skulsky, 1990) could be used to analyze how changes in the allocation of tasks to Decision Making Units affect organizational behavior. To perform the latter, existing algorithms for performance evaluation need to be modified.

This research will be performed by Mr. Didier Perdu under the direction of Dr. Levis.

Progress to Date: In the Petri Net representation of the feasible variable structures, task allocation is done by assigning transitions to decision making units (DMU). Adjacent transitions, belonging to one *branch* of the Petri Net, can be assigned to a single (DMU). However, tasks belonging to different branches cannot be allocated to the same DMU. Current research is focused on determining algorithms for task allocation. A simple example follows:

Example: Fair Algorithm

Step 1: Find the branch with the minimum number of layers, (i.e., the minimum number of fixed structure branches being folded), l_m .

Step 2: Assign 'n' number of DMUs to the branch with l_m layers.

Step 3: Any branch with l_i number of layers ($l_i > l_m$) is assigned $n \frac{l_i}{l_m}$ or $n \frac{l_i}{l_m}$ number of DMUs.

Once the probability distributions associated with the DTree are given, the algorithms can be modified to reflect a fair distribution of tasks among all DMUs. Similar such algorithms can be developed based on different criteria (different performance measures) for Task allocation. This is a future research issue. Tasks 2 and 3 are interdependent; folding procedures impacts task allocation and requirements (desired by user) for task allocation affect the folding procedures.

The above development assumes that each node of the DTree represents a unique physical entity, i.e., a sensor. This assumption need not be true as different sets of evidence, coming from the same sensor, may be represented by different nodes in the DTree. This has an effect on the process of building physical architectures from the functional ones, specifically on the folding to obtain a variable structure and on the task allocation processes. These questions pose long-term research issues.

5.0 MEETINGS

In May, Dr. Lehner and Dr. Levis attended the URI annual review meeting in Orlando, FL.

In June, Dr. Lehner presented papers at the Symposium on C2 Research and the C2 Decision Aids conference in Monterey, CA.

In June, Dr. Levis attended the 1992 IFAC/IFORS/IFIP/IEA Symposium on Man-Machine Systems held in The Hague, The Netherlands. Dr. Levis was the first author and presenter of one Plenary Paper and the co-author of another one (items 13 and 14 in Section 7.2)

6.0 RESEARCH PERSONNEL

6.1 Current Research Personnel

The following persons participated in this effort during this reporting period.

Prof Paul Lehner

Prof. Alexander H. Levis.

GMU - Co-Principal Investigator

GMU - Co-Principal Investigator

Mr. Didier Perdu

GMU - Graduate Student (PhD)

Mr. N. Thomas Lam	GMU - Graduate Student (PhD)
Mr. Syed Abbas K. Zaidi	GMU - Graduate Research Assistant (PhD)
Ms. Zhenyi Jin	GMU - Graduate Research Assistant (MS)
Mr. Zhuo Lu	GMU - Graduate Research Assistant (MS)
Mr. Diwakar Prabhakar	GMU - Graduate Research Assistant (MS)
Ms. Azar Sadigh	GMU - Graduate Research Assistant (MS)
Mr. Mathew Christian	GMU - Undergraduate Research Assistant

6.2 Previous Research Personnel

The following persons were previously supported by the research effort.

Mr. Bhashyam Nallappa	GMU - Graduate Research Assistant (MS)
Mr. Mir-Masood Seyed-Solorforough	GMU - Graduate Research Assistant (PhD)
Dr. Kent Hull	DSC
Dr. Martin Tolcott	DSC - Consultant
Dr. Theresa Mullin	DSC
Dr. Michael O'Conner	DSC - P.I. of subcontract
Mr. William Roman	DSC - Programmer
Mr. Steve Saks	DSC - Programmer
Dr. Michael Donnell	Consultant

6.3 Personnel Changes

Mr. Mathew Christian was hired as an undergraduate research assistant. Mr. Christian will complete his undergraduate degree in the Fall 1992, whereupon he will enter the GMU graduate program in Systems Engineering. A number of graduate students have joined the effort for the summer term (June to August).

7.0 DOCUMENTATION

7.1 Theses

Completed

1. S. A. K. Zaidi, "On the generation of Multilevel, Distributed Intelligence Systems using Petri Nets," MS Thesis. Report GMU/C3I-113-TH, C3I Center, George Mason University, Fairfax, VA November 1991. (Advisor: Prof. Levis)
2. Z. Lu, "Coordination of Distributed Intelligence Systems," MS Thesis. Report GMU/C3I-120-TH, C3I Center, George Mason University, Fairfax, VA, May 1992. (Advisor: Prof. Levis)

In Progress

3. MS Thesis by A. Sadigh - due December 1992. (Advisor: Prof. Lehner)

4. Ph.D. Thesis by T. Lam - due May 1993. (Advisor: Prof. Lehner)
5. MS Thesis by Z. Jin - due September 1993. (Advisor: Prof. Levis)

7.2 Technical Papers

1. Lam, N.T. and Lehner, P.E. "A Quantitative Model for Predicting the Usefulness of Decision Aids," *Proc. 1992 Conference on C2 Decision Aids*, Navy Postgraduate School, Monterey, CA, June 1992.
2. Lehner, P. "Towards a Theory of Team Design," *Proceedings of the 1991 Symposium on Command and Control Research*, June 1991, 149-159.
3. Lehner, P. "Towards a Prescriptive Theory of Team Design," *Proc. 1991 IEEE Int'l Conference on Systems, Man and Cybernetics*, October 1991, 2029-2034.
4. Lehner, P., Nallappa, B., O'Conner, M., Saks, S. and Mullin, T. "Cognitive Biases and Stress in Team Decision Making: Preliminary Report," *Proceedings of the 1991 BRG Symposium on Command and Control*.
5. Lehner, P. and Sadigh, A. "Reasoning under Uncertainty: Some Monte Carlo Results," in *Uncertainty in Artificial Intelligence: Proceedings of the Seventh Conference (1991)*, San Mateo: Morgan Kaufmann Publishers, 1991, 205-211.
6. Lehner, P.E. and Sadigh, A. "A Procedure for Compiling Influence Diagrams," *Proc. 1992 Symposium on C2 Research*, Navy Postgraduate School, Monterey, CA, June 1992.
7. Levis, A. H., "A Colored Petri Net Model of Intelligent Nodes" *Proc. 1991 IMACS Symposium on Modeling and Control of Technological Systems*, Lille, France, May 1991.
8. Levis, A. H., "A Colored Petri Net Model of Command and Control Nodes" to appear in *Command, Control, and Communications: Advanced Concepts and Paradigms*, Carl R. Jones, Ed., AIAA Press, Washington DC. Book to appear in late 1992.
9. Lu, Zhuo and A. H. Levis, "A Colored Petri Net Model of Tactical Decision Making," *Proc. 1991 Symposium on C2 Research*, National Defense University, Ft. McNair, Washington, DC, June 1991.
10. Lu, Zhuo and A. H. Levis, "A Colored Petri Net Model of Distributed Tactical Decision Making," to appear in *Proc. 1991 IEEE International Conference on Systems, Man, and Cybernetics*, October 1991.
11. Lu, Zhuo and A. H. Levis, "Coordination in Distributed Decision Making," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics*, October 1992.
12. Zaidi, S. A. K. and A. H. Levis, "Algorithmic Design of Multilevel Organizational Structures," *Proc. 1992 IEEE International Conference on Systems, Man, and Cybernetics*, October 1992.
13. Johannsen, G., A. H. Levis, and H. Stassen, "Theoretical Models in Man - Machine Systems and their Experimental Validation," *Proc. 1992 IFAC/IFIP/IFORS/IEA Symposium on Man-Machine Systems*, Pergamon Press, Oxford 1992 (to appear)

14. Levis, A. H., Neville Moray, and Baosheng Hu, "Task Allocation and Discrete Event Systems," *Proc. 1992 IFAC/IFIP/IFORS/IEA Symposium on Man-Machine Systems*, Pergamon Press, Oxford 1992 (to appear)

8. REFERENCES

- Buede, D.M. (1992) Superior design features of decision analytic software. *Computers and Operations Research*, 19(1), 43-58.
- Heckerman, D., Breese, J. and Horvitz, E. (1989) The compilation of decision models. in *Proceedings of the 1989 Workshop on Uncertainty in Artificial Intelligence*, 162-173.
- Remy, P. and Levis, A. H. (1988). "On the Generation of Organizational Architectures Using Petri Nets." in *Advances in Petri Nets 1988, Lecture Notes in Computer Science*, G.Rozenberg Ed. Springer-Verlag, Berlin, Germany.